Evidence of slow magneto-acoustic waves in photospheric observations of a sunspot

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ABSTRACT

We show the observational evidence for the presence of MHD waves in the solar photosphere deduced from SOHO MDI Dopplergram velocity observations. The magneto-acoustic oscillations are observed as acoustic power enhancement in the sunspot umbra at high frequency bands in the velocity component transverse to the magnetic field. We use numerical modelling of the wave propagation through localised non-uniform magnetic field concentration along with the same filtering procedure as applied to the observations to identify the observed waves. Underpinned by the results of the numerical simulations we classify the observed oscillations as slow magneto-acoustic waves excited by the trapped sub-photospheric acoustic waves. We consider the potential application of the presented method as a diagnostic tool for magnetohelioseismology.

Subject headings: Solar: photosphere, sunspots — helioseismology: acoustic oscillations, MHD, simulations

1. Introduction

Helioseismology, the study of acoustic 5 minute oscillation eigenmodes excited by the turbulence in the convection zone of the Sun, has been hugely successful in developing and testing the theories and models of solar interior (Duvall et al. 1997). The investigations of sunspots using methods of local helioseismology (Kosovichev & Duvall 1997; Zhao & Kosovichev 2006; Zharkov et al. 2007; Thompson & Zharkov 2008; Gizon et al. 2009), by analysing the properties of waves passing through these magnetic features, have provided us with a wealth of insight into the subphotospheric nature and, in many cases, have posed new questions concerning the understanding of sunspot structure.

So far, such studies have mostly concentrated on investigations of the effect of sunspot magnetic structure on the oscillations known to be present in the quiet Sun photosphere. At the same time, it is known from MHD theory that a number of different oscillatory modes are present in magneto-hydrodynamic atmospheres. In fact, it is argued (Moradi & Cally 2008; Moradi et al. 2009) that at least some of the inconsistencies in the helioseismic analyses of sunspots are due to the use of approximations disregarding these modes. Numerical MHD simulations are currently used to help us gain an insight into such questions (Crouch & Cally 2003; Shelyag et al. 2007, 2009; Parchevsky & Kosovichev 2007; Cameron et al. 2008; Khomenko et al. 2009). A

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variety of propagating and standing MHD waves (e.g., slow mode, Alfvén, and fast mode) have been observed higher in the outer atmosphere of the Sun, mainly in coronal loops, but also in other structures such as coronal plumes and prominences (Bogdan et al. 2003; Nagashima et al. 2007; Fedun et al. 2009). In addition, numerous observations obtained in different spectral lines revealed presence of three minute umbral oscillations from the transition region into the corona (e.g. Centeno et al. (2006); Banerjee et al. (2007)). However, little clear observational evidence of magneto-acoustic waves has been presented so far at the level of the solar photosphere (Zirin & Stein 1972; Dorotovič et al. 2008).

Based on the preliminary analysis of symbiosis of observational and simulated data, in this letter we show a first direct evidence of presence of slow magneto-acoustic waves in the sunspot umbra. Comparing the results of MHD forward modelling with the observations we confirm the correspondence of the the slow magneto-acoustic mode to the umbral power increase at high frequencies seen at large angles between the normal to the solar surface and the line of sight.

2. Data and Reduction

We used the data from NOAA Active Region 9787, consisting of single axisymmetric sunspot that showed little evolution during 20 - 28 January 2002, and observed continuously by the SOHO Michelson Doppler Imager (MDI) instrument. MDI uses the spectral line Ni-I 6776.772 Å originating at approximately 300 km height above the solar surface (Scherrer et al. 1995). The dataset, available on the European Helio- and Asteroseismology Network (HELAS) web site at `http://www.mps.mpg.de/projects/seismo/NA4/`, was prepared by HELAS and has been thoroughly described and analysed by Gizon et al. (2009). The images were remapped using Postel projection with a map scale of 0.12° to one $512 \times 512 \times 1440$ data cube of Doppler velocity data for each day. The centres of projection were chosen to track the motion of the sunspot (Carrington longitude of $\approx 133^\circ$ and latitude at 8.3° South). Over the nine days of observations the region travelled from 56° West to 61° East.

For each day of observation we calculate the temporal Fourier transform of the Doppler images. We then divide this into 1. mHz bandwidth intervals and calculate the oscillatory power averaged over each of these frequency bandwidths. The power is then normalised by the dominating quiet Sun acoustic power value. Figures 1 and 2 show the results for the 3 mHz and 6 mHz centred frequency bands, respectively.

3. Simulation

We used the code SAC (Sheffield Advanced Code) to carry out the forward simulations of sound wave propagation through a localised strong non-uniform magnetic field concentration, representing a sunspot. A detailed description of the code, numerical methods and the tests we used to show the robustness of the code and applicability of SAC to a wide variety of magneto-hydrodynamic problems are presented in Shelyag et al. (2008).

The code solves the full compressible system of equations of magneto-hydrodynamics in two or three dimensions on Cartesian grid. Hyperdiffusivity and hyperresistivity techniques are used to ensure the numerical solution is stable. The code also uses variable separation to conserve the magneto-hydrostatic equilibrium of the background unperturbed state.

Standard Model S (Christensen-Dalsgaard et al. 1996), slightly modified to achieve convective stability,

is used as the unperturbed "quiet", non-magnetic model of the solar interior. The physical size of the computational domain is 180 Mm in horizontal and 50 Mm in vertical direction. The domain is resolved by 960x1000 grid cells. The numerical domain is set such that the upper boundary is located right above the visible solar surface.

The boundaries of the domain are open, allowing the plasma to go into and out of the numerical domain freely. However, some weak reflection from the boundaries is observed due to non-ideality of the numerical representation of the boundary conditions.

A non-uniform non-potential self-similar static magnetic field configuration (see Shelyag et al. (2009) and references therein) is implemented in one half of the domain to mimic sunspot properties. The maximum vertical magnetic field strength is 3.5 kG at the level approximately corresponding to the visible solar surface. The magnetic field of this strength not only decreases the temperature in the sunspot at the solar surface, but also creates a layer with the ratio of local Alfvén speed to local sound speed greater than unity. This layer is responsible for acoustic and magneto-acoustic wave mode conversion.

We use a single spatially and temporally localised acoustic source to excite the oscillations in the domain. The source is located in the middle of the horizontal layer 500 km beneath the solar surface. This position of the source allows us to study the interaction of the wave packet, generated by the source, with unperturbed and perturbed by the magnetic flux tube halves of the numerical domain. Thus it also ensures to directly compare the character of the wave propagation in the magnetically active region with the quiet Sun region.

4. Results and Discussion

The results of the simulations have clearly shown the presence of an additional, "magnetic" mode. The mode is excited by the acoustic wave front passing through mode conversion region of the magnetic flux tube and clearly seen in the computed magnetic field perturbation. As is evident in the movies which can be found at `http://robertus.staff.shef.ac.uk/publications/acoustic/`, the mode is different in its nature and behaviour compared to acoustic wave packet as seen in non-magnetic quiet Sun simulations. By considering the velocities in non-magnetic and magnetic parts of the same simulation we have observed that this mode is more pronounced in the horizontal rather than vertical component. This can be clearly seen in Figure 3, where we have measured the acoustic power in the simulation box separately for horizontal and vertical velocity components, $P_{x|z}(x, z) = \int v_{x|z}^2(x, z, t)dt$ and then constructed the acoustic power ratios between "quiet" and "magnetic" parts of the simulation as function of horizontal coordinate and depth.

To investigate these oscillations further we consider vertical propagation of the waves at the centre of the flux tube by cross-correlating the near surface velocity component with deeper signal. At the centre of the flux tube the magnetic field is exactly vertical by construction, and, according to Syrovatskii & Zhugzhda (1967), propagation of slow magneto-acoustic wave with Alfvén wave-speed along the field line is expected. The results of cross-correlation are presented in Figure 4 for horizontal and vertical velocities. For both components, we can clearly see the (fast magneto-) acoustic wave packet arriving to the surface around negative time-lag, being reflected back to the interior for positive times. The correlation in horizontal velocity component also shows the second "slower" mode propagating along the z direction with Alfvén wave-speed. Since in our model the mode-conversion region, where Alfvén velocity is close to the local sound speed $v_A \approx v_s$, is located near the surface, we conclude that we observe the slow magneto-acoustic mode that propagates along the magnetic field lines.

From Figure 4 it follows that for an almost vertical magnetic field, the oscillating component of the slow magneto-acoustic mode will mainly contribute to the horizontal component of velocity. In our 2D model we can describe the line-of-sight velocity $v_{\mathrm{LOS}} = v_z \cos\alpha + v_x \sin\alpha$, where α is the angle between the normal to the surface and line-of-sight direction. Since in equatorial plane α is approximately equal to the heliographic longitude of the observed region, we can expect the stronger observable slow mode contribution at larger heliographic angles. The data in Figures 1 and 2 show the acoustic power ratios in frequency bands centred at 3 and 6 mHz measured from daily NOAA 9787 data from January 21 ($\alpha \approx 56°$ West), when the region was located close to the west limb, to January 24 ($\alpha \approx 3°$ West), when it was at the central meridian, to January 28 (close to east limb, $\alpha \approx 61°$ East). At 6 mHz we can clearly see the brightening at the central part of the sunspot, for the observations made close to the limb. No such effect is observed at 3 mHz. Also, ring-like structures of increased acoustic power are visible at the sunspot center at high frequencies at smaller heliographic angles, which suggests a possible signature of strong inclined fields.

Such observational frequency dependence is also supported by our numerical simulation. Figure 5 shows that the horizontal component oscillations inside the flux tube are strongly suppressed at 3 mHz, and enhanced at 6 mHz and above. Also in the vertical component the power increase at high frequencies is observed in the region where the magnetic field becomes slightly inclined. This could correspond to aforementioned ring like structures seen at high frequencies in observations close to the central meridian.

In order to verify our results, we consider the possible artifacts that might be present in the near limb data and can potentially affect the results of the analysis. SOHO/MDI are known to suffer from low light level "saturation" problem as well as from limitations of on-board processing algorithm. We have carefully considered the following potential artifacts: pixel rotation, low light levels and limitations of on-board processing algorithm (Liu & Norton 2001). Firstly, the pixel rotation does not cause a problem at the limb where the slow mode measurements are carried out. Also, following Scherrer (1993) we have implemented the on-board algorithm, and using the intensity data from continuum observations, we have run several test simulations with varying noise levels. The results have shown little or no ill effect for acoustic power computation. Thus, we conclude that the acoustic power measurements derived from SOHO/MDI instrument are not affected by such issues.

5. Conclusions

We have found observational evidence for slow magneto-acoustic waves deduced from high frequency acoustic power maps constructed from near-the-limb observations where the observed Doppler shifted velocity signal has strong horizontal, i.e. perpendicular to magnetic field, component. This behaviour agrees with the description of the slow MHD mode in the strong magnetic field approximation. Thus, supported by our forward simulations, we argue that the acoustic wave packet passing through the flux tube, when travelling through the conversion region $v_A \approx v_s$, splits into fast and slow magneto-acoustic waves. The fast magnetoacoustic wave passing through the tube transforms back to the acoustic mode, while the slow mode travels along the field lines up and down.

The presence of slow waves at this level appears to support the link between recently reported coronal slow waves and photospheric processes. Though further investigation and insight into these processes are needed, the results of our simulation indicate how the energy contained in the acoustic wave is split between the slow and fast magnetoacoustic waves when passing through a magnetised region. From the arguments above, it seems natural to assume that at least partly these waves will travel along the field lines up to the

upper regions of sunspot atmosphere.

The fact that such slow oscillations are better pronounced in the direction normal to the magnetic field, opens a number of interesting questions and possibilities for helioseismic analysis of sunspot properties. For example, this approach allows us to investigate the dependency between magnetic field angle at the surface, line of sight and oscillatory power, thus potentially providing information about magnetic field inclination.

Finally, in this work we have used a HELAS dataset of over nine days of continuous observations of an isolated large and stable sunspot located at relatively low latitude. Preliminary analysis of near limb observations of the active region NOAA 8038 containing an isolated sunspot has shown features similar to the presented in this Letter. It is a matter of future research to develop this analysis further and to extend it to other more extensive observations. Also, it would be most interesting to investigate slow magnetic waves travelling up reaching the sunspot atmosphere and relating those to the observed atmospheric slow MHD waves.

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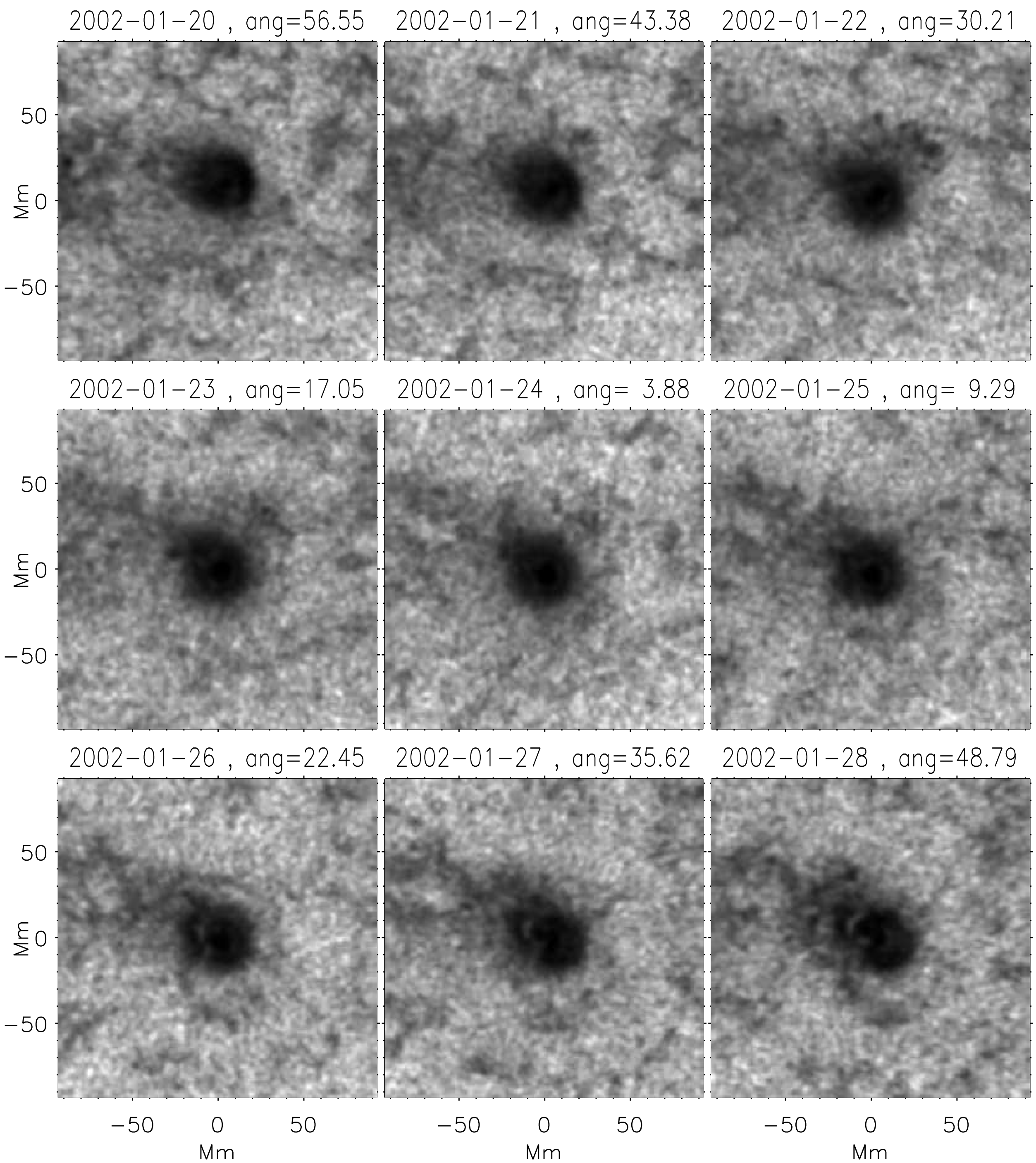

Fig. 1.— Acoustic power estimated from the line-of-sight velocity data for the NOAA AR9787 region. The data are taken at 9 subsequent snapshots as the sunspot travels from 56° West to 61° East on the solar surface. The data are frequency-filtered with the filter frequency band centered on 3 mHz. The images show little apparent variation in the centre of the sunspot.

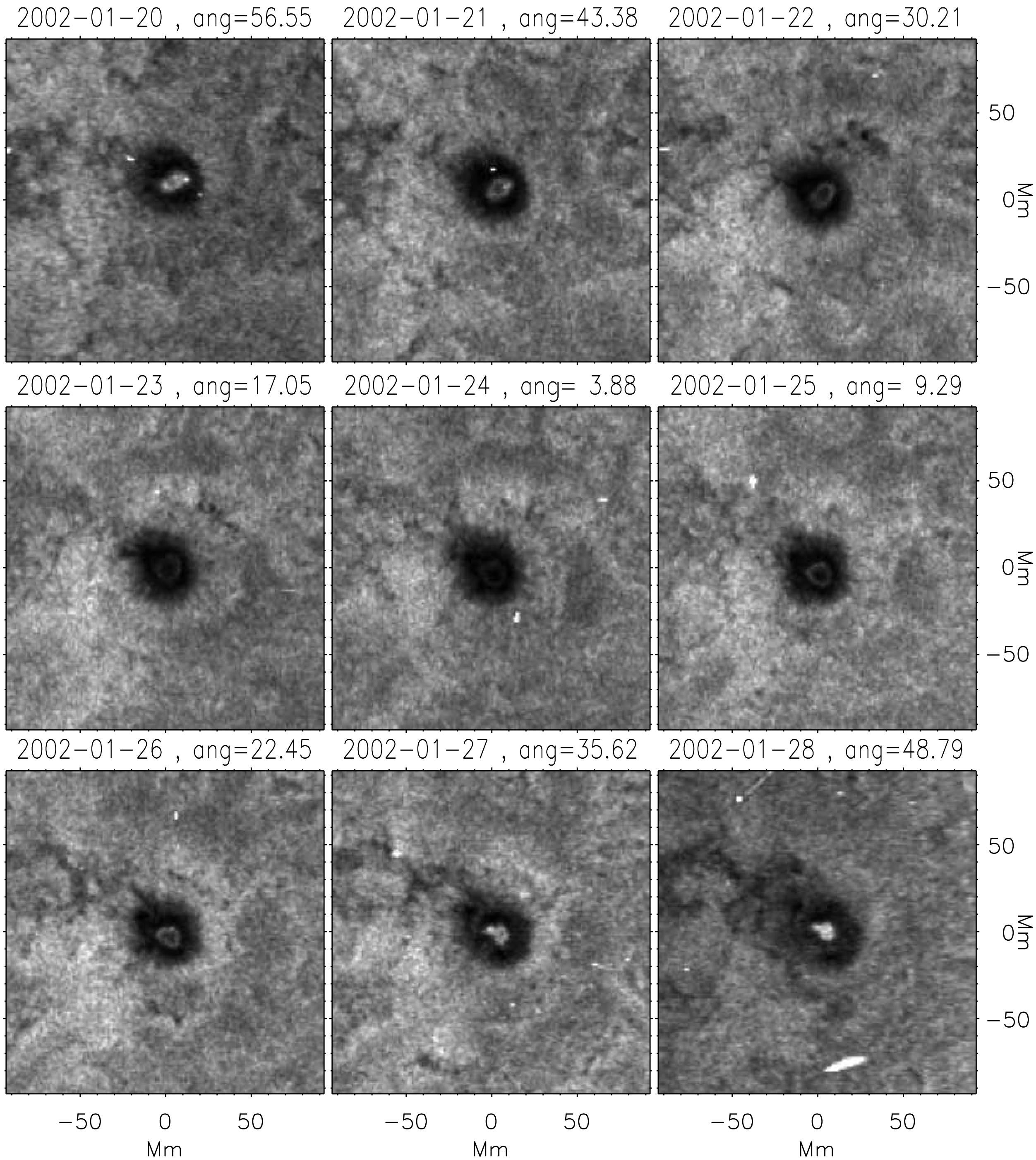

Fig. 2.— As Figure 1 but for the frequency band centered 6 mHz. The images show a significant variation dependent on the heliographic angle and reveal easily noticeable power enhancement inside the sunspot at large angles from the solar disk centre (first and last frames of the panel).

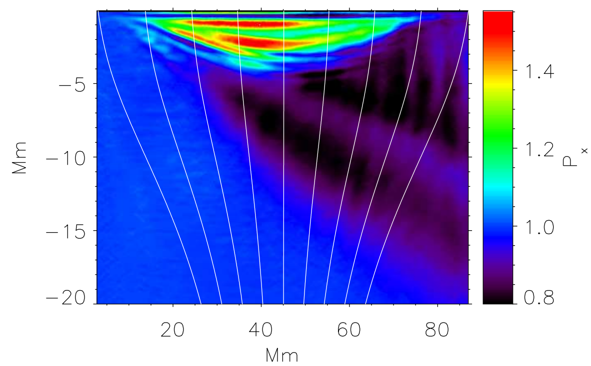

Fig. 3.— Horizontal (left panel) and vertical (right panel) acoustic power ratios between the quiet and magnetic parts of the synthetic data obtained by means of forward modelling. The magnetic field lines are overplotted. Strong absorption is observed in the vertical acoustic power in the magnetised region, while the horizontal power component shows a strong enhancement. Note that the images are not isotropic thus the magnetic field lines in the plots do not show the actual inclination of the magnetic field in the model.

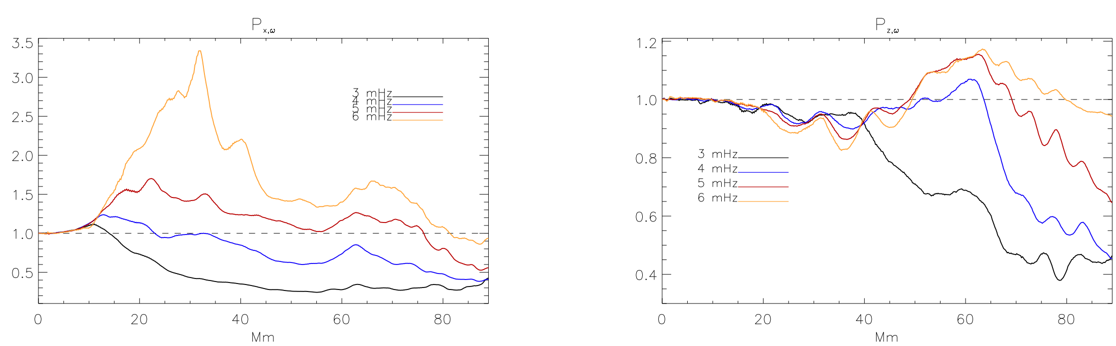

Fig. 4.— Simulation cross-correlation in v_x (left panel) and v_z (right panel) at the center of the magnetic flux tube as a function of depth. The arriving fast magneto-acoustic wave and reflected slow wave can be seen in the v_x cross-correlation, however, the fast wave dominates the v_z cross-correlation image. The theoretical time-distance curve for the wave propagating with Alfvén velocity is overplotted on the left panel, and time-distance curve for the wave propagating with local sound speed is overplotted on the right one.

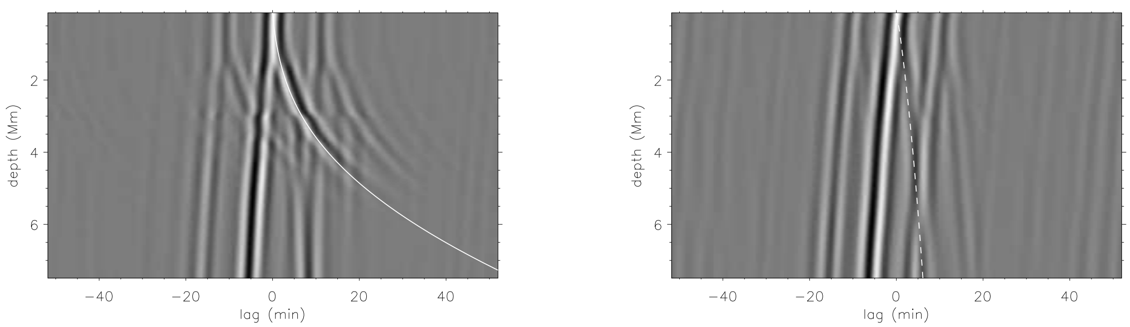

Fig. 5.— The acoustic power ratio in horizontal (left plot) and vertical (right plot) velocity components, filtered using the same filters as applied to observational data and described in Section 2. A strong power enhancement at 6 mHz in horizontal velocity component is observed, which corresponds to the power enhancement seen in the 6 mHz filtered observations (see Fig. 2). Again, no power enhancement is observed in the 3 mHz frequency band (cf. Fig. 1).